MAGNETICALLY DELAYED LOW-PRESSURE GAS DISCHARGE SWITCHING

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Abstract

We have investigated the properties of a magnetically delayed, low-pressure gas discharge switch. We performed measurements of the closure and recovery properties of the switch; performed quantitative erosion measurements; and observed the onset of x-ray production in order to compare switch properties with and without delay. Further, we performed qualitative optical measurements of transition line spectra to correlate our electrical recovery measurements with plasma deionization.

Introduction

Fast-closure-rate, high-voltage (>100 kV), high-current (>10 kA), high-repetition-rate (>1 kHz) switching has remained a major area of research in the pulsed power field [1-3]. Solid-state switching has generally been limited to several tens of kilovolts; high-pressure gas discharge switching is limited to repetition rates below 1 kHz; vacuum switching is generally a slow closure process; and magnetic switching requires extremely precise voltage and reset state control to minimize jitter.

Low-pressure gas discharge switches have shown promise as a fast-closing, high-repetition-rate device such that if sufficiently fast closure times can be achieved, single-stage power conditioning chains would become feasible [4,5]

The primary difficulty with this switch, however, is anode electrode damage during closure initiation, resulting in short lifetimes. Once triggered, electrons emitted from the cathode plasma can form a pinched beam and deposit enough localized energy to vaporize anode material. Inserting a series delay element, which inhibits the application of full voltage and current until such time that the discharge plasma has filled the gap, minimizes this effect. It is this version of the low-pressure switch that we are presently studying.

Our magnetically delayed low-pressure switch (MDLPS) test-stand was built primarily to support the long-pulse, relativistic klystron (RK) and free electron laser (FEL) work at Lawrence Livermore National Laboratory (LLNL) [6]. In this application, a closing switch initiates a pulse, which is delivered to an induction accelerator cell [7]. The induction cell accelerates an injected electron beam to a sufficient energy suitable for the RK or FEL.

Apparatus

The MDLPS test-stand (Fig. 1) consists of a single water-filled, 12 Ohm, 70 ns Blumlein

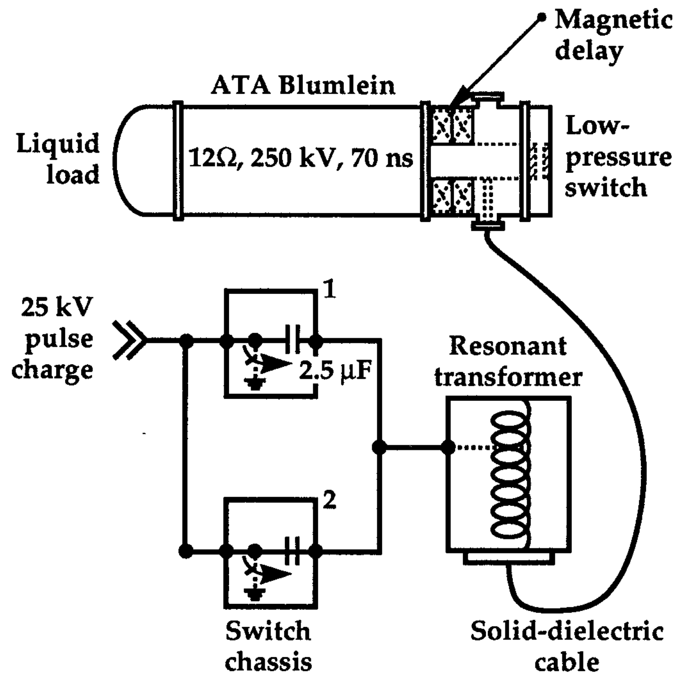

Figure 1. Switch test-stand used to study magnetically delayed switch properties.

from the Advanced Test Accelerator at LLNL. The Blumlein is attached to a liquid load and charged from a single dual-resonant transformer. The transformer is powered by two charged capacitor banks discharged through separate thyratrons, diode isolated and fired sequentially to produce two charging pulses. A trigger pulser initiates a single closure event at the peak of the first charging pulse; the second, variable timing, charging pulse is allowed to ring to zero and is used as a test pulse to verify gap recovery.

The low-pressure gas gap consists of an anode-cathode electrode pair separated a sufficient distance to prevent self breakdown (at approximately 100 to 150 kV/cm). A surface flashover triggering device, embedded within the cathode, initiates the ionization processes that render the gas highly conductive. A saturable inductor placed in series with the switch, delays the onset of full current, allowing the ionization processes to spread throughout the gap volume prior to full closure. The saturable inductor is designed to limit current flow below the threshold for constricted discharges, and hold off the full anode-cathode voltage until the discharge has filled the gap volume.

Diagnostics for the test-stand consisted of current and voltage sensors for the switch and

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14. ABSTRACT
We have investigated the properties of a magnetically delayed, low-pressure gas discharge switch. We performed measurements of the closure and recovery properties of the switch; performed quantitative erosion measurements; and observed the onset of x-ray production in order to compare switch properties with and without delay. Further, we performed qualitative optical measurements of transition line spectra to correlate our electrical recovery measurements with plasma deionization.

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Blumlein. Other diagnostics consisted of a fast x-ray detector, a fast gated camera, and a 0.25m monochromator. At preset, we used an image intensified gated camera to observe the monochromator output. We are installing a gated photomultiplier system for future work.

Experiments

We performed standard parametric studies of the magnetically delayed low-pressure switch and compared the performance with and without the saturable inductor. A comparison of typical closure properties is shown in Fig. 2, and of typical recovery properties in Fig. 3. For these data, the gap spacing was 1 cm, the gas was nitrogen, and the anode-cathode voltage was 90 kV.

Closure time, defined as the 10 to 90% transition time of the voltage across the low-pressure gas gap, showed a factor-of-two improvement at lower pressures with the magnetic delay, i. e., with the saturable inductor. At higher pressures, above approximately 7 mT, the saturable inductor had little effect.

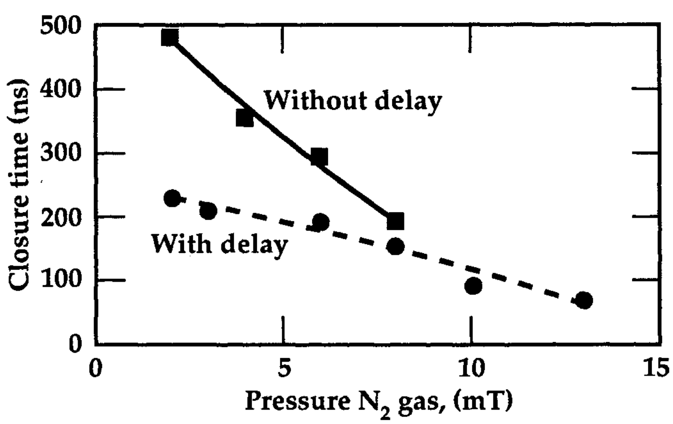


Figure 2. Measured closure results with and without delay.

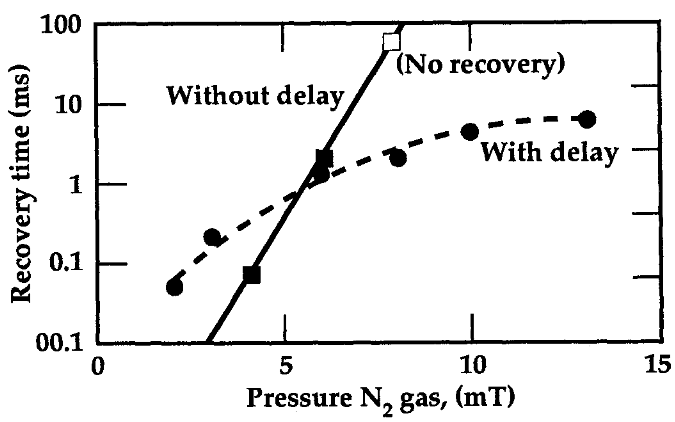
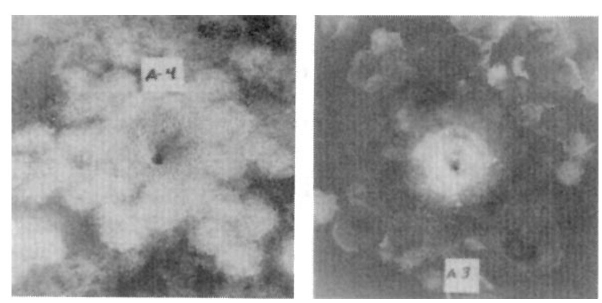


Figure 3. Electrically measured recovery results.

Recovery time with the series saturable inductor improved significantly and was extremely reliable: 99% recovery probability was estimated. At lower pressures, extremely good recovery times (approximately 50 µs or 20 kHz-equivalent pulse repetition frequency) were observed, while at higher pressures, recovery time was observed to be about 5 ms. By contrast, recovery probability without the series saturable inductor was not reliable and was measured to be between 80 and 90%. Although at lower pressures and this recovery probability, faster recovery times were observed, recovery did not occur above 7 mT without the series saturable inductor.

We made qualitative spectroscopic measurements of late-time line emission from the gap in order to verify our recovery measurements performed electrically. Spectroscopic observations of the discharge showed that line radiation from the nitrogen decayed within 10 µs after current cessation. Line radiation characteristic of the anode material, however, required greater than 50 µs to decay. This result was consistent with our electrical measurements.

Erosion rates with the series saturable inductor were a factor of 60 less than those of a similar lifetime test without the series saturable inductor. Photographic comparisons are shown in Fig. 4. These tests were conducted at 90 kV, with nitrogen at 8 mT pressure and using aluminum anodes. In the first test (Fig. 4a), severe anode damage was observed over the entire surface of the electrode and particularly across from the trigger electrode. The total number of shots was approximately 16,000. In the second test (Fig. 4b), a less pronounced indentation resulted from the test, with minimal damage having occurred throughout the anode surface. The total number of shots during this latter test was approximately 400,000.



(a) (b)

Figure 4. Comparison of electrode erosion (a) without and (b) with magnetic delay.

We performed x-ray measurements (Fig. 5) to understand the time evolution of electron emission from the cathode of the low-pressure switch. Our relative measurements of the integrated x-ray output during switch closure showed an order-of-magnitude decrease with the series saturable inductor. Further, we observed the most intense x-ray output from the low-pressure switch during the initiation or trigger delay period without the series saturable inductor, and after the closure process had begun with the series saturable inductor.

We also measured the variation of the x-ray output from the gap at various gas pressures. From this measurement, we observed the x-ray output decrease by about 30% when the gas pressure was increased from 1 to 9 mT.

(a)

(b)

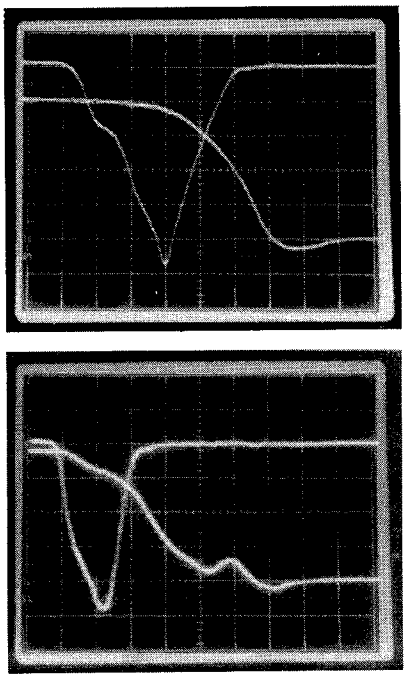


Figure 5. Measured x-ray pulse (top traces) of the low-pressure switch (a) without magnetic delay (0.5 V/div.) and (b) with magnetic delay (0.1 V/div.). Pressure was 8 mT, N_2 gas; gap spacing was 1 cm. Bottom traces are anode fall. Horizontal scales are 100 ns/div.

Modeling

We developed a one-dimensional model for the closure regime of the low-pressure switch. In this model, the motions of ions and electrons are modeled by fluid equations that include collision ionization and space charge effects. The model equations are parameterized in terms of gas type (ionization coefficient) and pressure; switch gap length; and cross-sectional area. This model permits us to follow the space-time evolution of the electric field; the potential; and the ion and electron current densities in the gap, as well as the total switch current and anode voltage during switch closure.

We have implemented the model in a general-purpose network and system simulation code. This implementation permits the construction of a detailed system simulation model of the test-stand that includes the charging circuit, Blumlein, magnetic switch, and load. We use a magnetic switch model that includes rate-dependent loop-widening of the hysteresis loop, hysteretic losses, minor loops, and hysteresis effects [8]. Presently, we are validating the low-pressure switch and magnetic switch models against experimental data. Once validated, the complete system model should permit us to study the sensitivity of switch closure performance to magnetic core parameters and to low-pressure switch parameters such as gas type and pressure; and electrode spacing; thereby providing us a tool for making switch design tradeoffs. The details of the switch model is the subject of a future paper.

Conclusions and Future Work

We have demonstrated that the use of a series saturable inductor placed in series with a low-pressure gas spark gap greatly enhances performance. From our measurements, we understand this improved performance to be primarily due to minimizing anode material vaporization during the initial closure of the gap. Without the series saturable inductor, x-ray emission occurs from the point of triggering until the initial collapse of the gap impedance. The energy deposition into the anode is large as determined by the integrated x-ray intensity. With the series saturable inductor, energy deposition into the anode is initiated at the instant the collapse of the gap impedance occurs. The net effect is lower energy deposition into the anode. From our data, we conclude that with our present triggering method, this switch is capable of operating as either a low-repetition-rate final output switch or, because of the slower closure times at low pressure, as a high-repetition-rate initial commutation switch, i.e., in the initial stages of the power conditioning chain. Although the present triggering device appears adequate, it is difficult to couple a significant portion of the trigger electrical energy into the low-pressure gas. In future work, we will install newly developed, simple, ferroelectric electron emitters as a triggering device [9]. Current densities from 0.1 to 1 kA/cm^2 have been extracted from such an emitter for several hundred nanoseconds. Such a device should allow better coupling of the trigger electrical energy to the low-pressure gas. We would therefore expect much faster closure times even at lower pressures.

Our spectral observations indicate that recovery is primarily inhibited by anode vapor remaining ionized in the gap. It is well established that recombination times for metal vapor exceed those of gasses by at least an order of magnitude. Thus, to enhance recovery, we will investigate the use of anode materials with low heat of vaporization, in order to minimize the accumulation of anode material vapor in the gap.

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